Frictionless Technology Diffusion: The Case of Tractors

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Abstract

Empirical evidence suggests that there is a long lag between the time a new technology is introduced and the time at which it is widely adopted. The conventional wisdom is that this fact is inconsistent with the predictions of the frictionless neoclassical model. In this paper we show this to be incorrect. Once the appropriate driving forces are taken into account, the neoclassical model can account for 'slow' adoption. We illustrate this by developing an industry model to study the equilibrium rate of diffusion of tractors in the U.S. between 1910 and 1960.

1 Introduction

Understanding the determinants of the rate at which new technologies are created and adopted is a critical element in the analysis of growth. Even though modeling equilibrium technology creation can be somewhat challenging for standard economic theory, understanding technology adoption should not be. Specifically, once the technology is available, *the adoption decision is equivalent to picking a point on the appropriate isoquant.* Dynamic considerations make this calculation more complicated, but they still leave it in the realm of the neoclassical model. A

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simple minded application of the theory of the firm suggests that profitable innovations should be adopted instantaneously, or with some delay depending on various forms of cost of adjustment.

The evidence on the adoption of new technologies seems to contradict this prediction. Jovanovic and Lach (1997) report that, for a group of 21 innovations, it takes 15 years for its diffusion to go from 10% to 90%, the 10-90 lag. They also cite the results of a study by Grübler (1991) covering 265 innovations who finds that, for most diffusion processes, the 10-90 lag is between 15 and 30 years.[1]

In response to this apparent failure of the simple neoclassical model, a large number of papers have introduced 'frictions' to account for the 'slow' adoption rate. These frictions include, among others, learning-by-doing (e.g. Jovanovic and Lach (1989), Jovanovic and Nyarko (1996), Greenwood and Yorukoglu (1997), Felli and Ortalo-Magné (1997), and Atkeson and Kehoe (2001)), vintage human capital (e.g. Chari and Hopenhayn (1994) and Greenwood and Yorukoglu (1997)), informational barriers and spillovers across firms (e.g. Jovanovic and Macdonald (1994)), resistance on the part of sectoral interests (e.g. Parente and Prescott (1994)), coordination problems (e.g. Shleifer (1986)), search-type frictions (e.g. Manuelli (2002)) and indivisibilities (e.g. Greenwood, Seshadri and Yorukoglu (2004)).

In this paper we take, in some sense, one step back and revisit the implications of the neoclassical frictionless model for the equilibrium rate of diffusion of a new technology. Our model has three features that influence the rate at which a new technology is adopted: changes in the price of inputs *other* than the new technology, changes in the *quality* of the technology, and endogenous *selection* of firms (managers).[2] The application that we consider throughout is another famous case of 'slow' adoption: the farm tractor in American agriculture. Following Lucas (1978), we

[1] There are studies of specific technologies that also support the idea of long lags. Greenwood (1997) reports that the 10-90 lag is 54 years for steam locomotives and 25 years for diesels, Rose and Joskow's (1990) evidence suggest a 10-90 lag of over 25 years for coal-fired steam-electric high preasure (2400 psi) generating units, while Oster's (1982) data show that the 10-90 lag exceeds 20 years for basic oxygen furnaces in steel production. However, not all studies find long lags; using Griliches (1957) estimates, the 10-90 lag ranges from 4 to 12 years for hybrid corn.

[2] Given our focus, we ignore frictions that can explain the change in prices and the (maybe slow) improvement in the technology. We do this because our objective is to understand the role played by frictions on the adoption decision, given prices and available technology.

study an industry model in which managers (farm operators) differ in terms of their skills. We assume that the technology displays constant returns to scale in all factors, including managerial talent. In order to eliminate frictions associated with indivisible inputs, we study the case in which there are perfect rental markets for all inputs.[3] Each farm operator maximizes profits choosing the mix of inputs. Given our market structure, this is a static problem. In addition, each manager has to make a discrete location choice: stay and continue farming, or migrate to an urban area and earn urban wages. We assume that migration is costly and, in fact, the cost of migration is the only non-convexity in our setting. The migration decision is dynamic. We take prices and the quality of all inputs as exogenous and we let the model determine the price of one input, land, so as to guarantee that demand equals the available stock.

We calibrate the model so that it reproduces several features of the U.S. agricultural sector in 1910. We then use the calibrated model, driven by exogenous changes in prices, to predict the number the tractors (and other variables) for the entire 1910-1960 period. The model is very successful at accounting for the diffusion of the tractor and the demise of the horse. The correlation coefficient between the model's predictions and the data is 0.99 for tractors and 0.98 for horses. We conclude that there is no tension between a frictionless neoclassical model and the rate at which tractors diffused in U.S. agriculture: the reason why diffusion was 'slow' is because it was not cost effective to use tractors more intensively.

In order to ascertain what are the essential features of the model that account for such a good fit, we study several counterfactuals. We analyze versions of the model that keep wages, horse prices and tractor quality fixed at their 1910 levels, and another version that ignores selection of firms (farmers) out of the industry. These alternative specifications fail to match the data in several important dimensions.

The paper is organized as follows. In section 2 we present a brief historical account of the diffusion of the tractor and of the price and quality variables that are the driving forces in our model. Section 3 describes the model, and Section 4 discusses calibration. Sections 5 and 6 present our results, and section 7 offers some concluding comments.

[3] This, effectively, eliminates the indivisibility at the individual level. Given the scale of the industry that we study, indivisibilities at the aggregate level are not relevant.

2 Some History

This section presents some evidence the use of tractors and horses by U.S. farmers, on the behavior of wages and employment in the U.S. agricultural sector, and on the changes in the size distribution of farms.

Diffusion of the Tractor. The diffusion of the tractor was not unlike most other technologies, it had a characteristic S-shape. Figure 1 plots the number of tractors on American farms. Diffusion was slow initially. The pace of adoption speeds up after 1940.

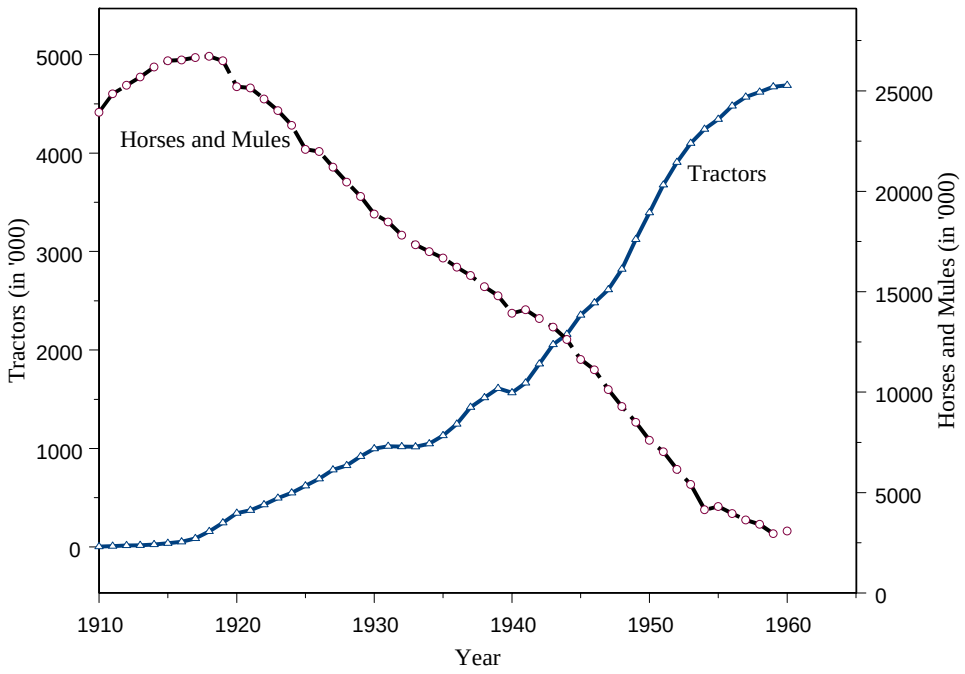

Figure 1: Horses, Mules and Tractors in Farms, 1910-1960

As the tractor made its way into the farms, the stock of horses began to decline. In 1920, there were more than 26 million horses and mules on farms. Thereafter, this stock began to decline and by 1960, there were just about 3 million. While the tractor was primarily responsible for this

decline, it should be kept in mind that the automobile was also instrumental in the elimination of the horse technology. As in the case of other technologies, investment in horses —the 'dominated' technology— was positive, even as the stock declined.

Real Prices for Tractors and Horses. Figure 2 plots the real price of a mid-size tractor and a pair of draft horses between 1910 and 1960.[4] Between 1910 and 1920, there is a sharp decline in the price of tractors which is partially reversed in the 1930s. In the 1940s and 1950s prices are lower and comparable to those prevailing in 1920s. One simple conclusion from this evidence is that farmers should have adopted tractors in 1920 at the same rate they did in the 1940s and 1950s. They did not. This observation lies behind the idea that adoption was slow. White (2000) collected data on some tractor characteristics and estimated a quality adjusted price for a tractor. The resulting series —labeled Tractor-quality adjusted in Figure 2— shows a steep decline until the mid-1920s, but very small changes after this. Thus, changes in the price of the technology —in the absence of frictions— appear to be insufficient to explain the pattern of adoption documented in Figure 1.

Farm Real Wage Rates and Employment. Real wages in the agricultural sector remained stagnant from 1910 till about 1930, fell by half between 1930 and 1934, and then doubled between 1940 and 1950. If the tractor was labor-saving, rising wages after 1940 would likely speed up adoption since holding on to the more labor intensive horse technology will be unprofitable. The falling wages in the early thirties might also go towards explaining the reluctance of farmers to switch to tractors during the same time period.

Man-hours on farms remained fairly constant between 1910 and 1930, and then fell by 76% between 1930 and 1970. Farm population decreased dramatically too. In 1910, there were 11.67 million farm workers (full-time equivalents). By 1960, this number had fallen to 5.97 million.

Distribution of Land-Holding Patterns. The distribution of land-holding patterns underwent a significant change between the years 1910 and 1960. The average size of a farm more than doubled, and land in large-sized farms (size above 1000 acres) tripled between 1920 and 1960. Land in mid-size farms (500-999 acres in size) also increased, though the increase was far less

[4] The data are from Olmstead and Rhode (2001). We thank Paul Rhode for providing the data.

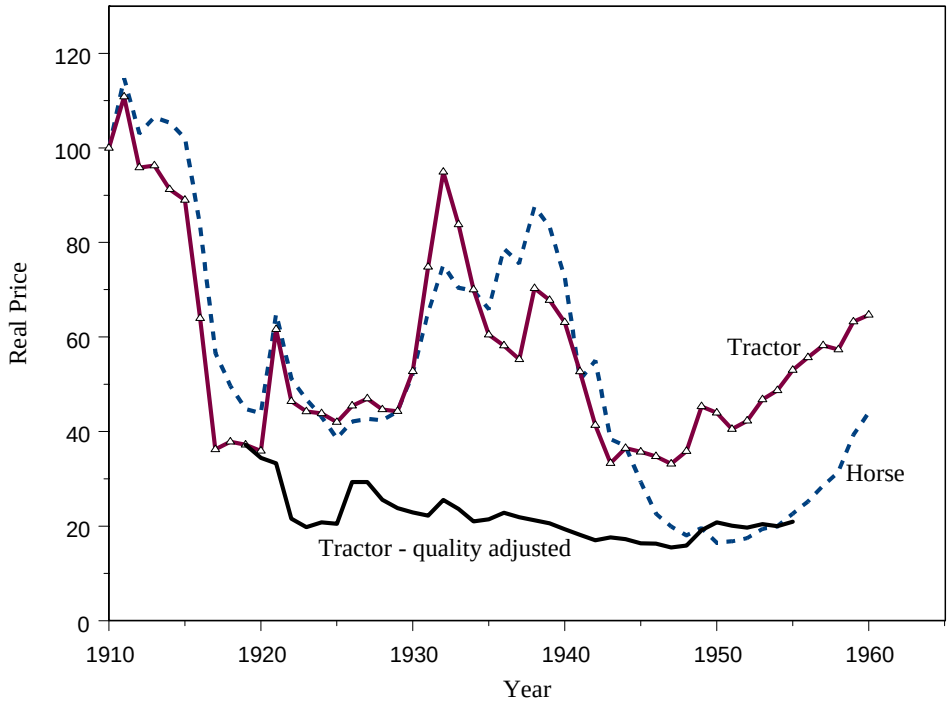

Figure 2: Real Prices for Tractors and Horses. 1910-1960

spectacular than its larger counterparts. As expected, land in smaller farms of size less than 500 acres decreased, with most of the decline after 1940.

Alternative Explanations. The standard approach to studying the diffusion of the tractor is based on the 'threshold' model. In its simplest form, the model takes as given the size of the farm (in acres) and considers the costs of different combinations of horse-drawn and tractor-drawn technologies required to produce a given amount of services. By choosing the cost minimizing technology, the model selects the type (size) of farm that should adopt a tractor. The predictions of the model — given the size distribution of farms — are then compared with the data. These calculations find that in the 1920's and early 1930's, U.S. farmers were too slow to adopt the relatively new tractor technology. Allowing for imperfect capital markets (Clarke (1991)) or

introducing uncertainty about the value of output (Lew (2001)) help improve the fit of the model, but not to the point where it is consistent with the evidence.

More recently Olmstead and Rhode (2001) estimate that changes in the price of horses and in the size distribution delayed, to some extent, the adoption of tractors. In their model the size distribution is exogenous. White (2000) emphasizes the role of prices and quality of tractors. Using a hedonic regression, he computes a quality-adjusted price series for tractors. White conjectures that the increase in tractor quality should be taken into account to understand adoption decisions.

3 A Simple Model of Farming and Migration

Our approach is to model technology adoption using a standard profit maximization argument, supplemented by a simple model of migration-choice along the lines of Becker (1964) and Sjaastad (1962). We consider a setting in which farm operators are heterogeneous. Each individual has a level of 'farm organizational ability' or 'skill' denoted by e. The distribution of skills in the population of *potential* farmers is given, and denoted by μ. However, the distribution of skills among *actual* farmers is endogenously determined by the model. In each period, a farmer can either stay (and farm) or migrate to an urban area. To simplify the analysis, we assume that the migration decision is irreversible: once a farmer leaves the rural sector, he cannot return to farming.[5]

If the farmer decides to stay, and operate the farm, he needs to decide how many tractors, horses, acres of land and labor to *rent* in spot markets. We consider the case in which there are *perfect* markets for all inputs. Thus, as is standard in the theory of the firm, indivisibilities at the individual farm level are irrelevant.[6] This implies that our model can be used to predict the total number of tractors but not their distribution across farms.

[5] Given the relevant values of the cost of migration and the potential gains of reverse migration, we will argue later that this is not as extreme an assumption as it sounds. The assumption that migration is irreversible eases the computation of the transitional path as we then do not have to verify all possible sequences of moves from and to the farm sector in analyzing the dynamics of the transition to the new steady state.

[6] Olmstead and Rhode (2001) provide evidence of the prevalence of contract work, i.e. of instances in which a farmer provides 'tractor services' to other farms.

Each farmer maximizes the present discounted value of utility taking prices as given. If the individual is in the farm sector, he chooses, in every period, the quantity of tractor, horse, land and labor *services* in order to produce agricultural output. The one period profit of a farmer with managerial skill level e is given by,

$$\begin{aligned}\pi_t(q_t, c_t, w_t^F, e) \quad \equiv \quad & \max_{k_t, h_t, n_t, a_t} p_{ct} F(k_t, h_t, n_t, a_t, e) - \\ & \sum_{\tau=-\infty}^{t} [q_{kt}(\tau) + c_{kt}(\tau)] m_{kt}(\tau) - [q_{ht} + c_{ht}] h_t - w_t^F \bar{n}_t - [q_{at} + c_{at}] a_t,\end{aligned}$$

where $F(k_t, h_t, n_t, a_t, e)$ is a standard production function which we assume to be homogeneous of degree one in all inputs, including managerial skill, e,[7] k_t is the demand for *tractor services*, h_t is the demand for *horse services* (which we assume proportional to the stock of horses), $n_t = (n_{ht}, n_{kt}, n_{yt})$ is a vector of labor services corresponding to three potential uses: operating horses, n_{ht}, operating tractors, n_{kt}, or other farms tasks, n_{yt}, and a_t is the demand for land services (which we assume proportional to acreage), and $\bar{n}_t = n_{ht} + n_{kt} + n_{yt}$ is the total demand for labor.

On the cost side, $q_{ht} + c_{ht}$ is the full cost of operating a draft of horses. The term q_{ht} is the rental price of a horse, and c_{ht} includes operating costs (e.g. feed and veterinary services). The term $q_{at} + c_{at}$ is the full cost of using one acre of land, and w_t^F is the cost of one unit of (farm) labor. Effective one period rental prices for horses and land (two durable goods) are given by

$$q_{jt} \equiv p_{jt} - \frac{(1 - \delta_{jt}) p_{jt+1}}{1 + r_{t+1}}, \qquad j = h, a,$$

where δ_{jt} are the relevant depreciation factors, and r_t is the interest rate.

Since we view changes in the quality of tractors as a major factor driving the decision to adopt the technology, we specified the model so that we could capture such variations. Specifically, we assume that tractor services can be provided by tractors of different vintages according to

$$k_t = \sum_{\tau=-\infty}^{t} m_{kt}(\tau) \tilde{k}_t(\tau),$$

[7] The assumption that F depends on managerial skill, e, follows the work of Lucas (1978). As in Lucas' framework, its main role is to endogenously generate changes in the size distribution of farms. Consequently, e should not be equated with education, but rather with the farm size.

where $\tilde{k}_t(\tau)$ is the amount of tractor services provided by a tractor of vintage τ (i.e. built in period τ) at time t, and $m_{kt}(\tau)$ is the number of tractors of vintage τ operated at time t. We assume that the amount of tractor services provided at time t by a tractor of vintage τ is given by,

$$\tilde{k}_t(\tau) \equiv v(x_\tau)(1-\delta_{k\tau})^{t-\tau},$$

where $\delta_{k\tau}$ is the depreciation rate of a vintage τ tractor, and $v(x_\tau)$ maps model-specific characteristics, the vector x_τ, into an overall index of tractor 'services' or 'quality.' Thus, our model assumes that the characteristics of a tractor are fixed over its lifetime (i.e. no upgrades), and that tractors depreciate at a rate that is (possibly) vintage specific. The rental price of a tractor is given by

$$q_{kt}(\tau) = p_{kt}(\tau) - \frac{p_{kt+1}(\tau)}{1+r_{t+1}},$$

where $p_{kt}(\tau)$ is the price at time t of a $t-\tau$ year old tractor, while the term $c_{kt}(\tau)$ captures the variable cost (fuel, repairs) associated with operating one tractor of vintage τ at time t.

The function $\pi_t(q_t, c_t, w_t^F, e)$ captures the payoff in period t to being a farmer. Instead of farming, an individual with skill level e can make an (irreversible) migration decision. If he chooses to migrate to an urban area at time t, he receives a payoff given by

$$V_t^U \equiv \sum_{j=0}^{\infty} R_t(j) w_{t+j}^U - \varphi,$$

where w_{t+j}^U is a measure of the utility associated with working in an urban area at time $t+j$, φ is the fixed cost of migration, and

$$R_t(j) = \begin{cases} 1 & if\ j=0 \\ \Pi_{s=1}^{j}(1+r_{t+s})^{-1} & if\ j \geq 1 \end{cases},$$

is the relevant discount factor.

It follows that the utility of an individual with skill e who starts period t in a rural area (i.e. is a potential farmer) satisfies the following Bellman equation

$$V_t(e) = \max\left\{V_t^U, \pi_t(e) + R_t(1)V_{t+1}(e)\right\}.$$

Given our assumption that F is increasing in e, it follows that $V_t(e)$ is also increasing in e. Moreover, if a farmer with skill level e chooses not to migrate, then all farmers with skill level

$e' \geq e$ will not migrate either. Put differently, equilibrium migration is fully described, for each t, by the level of skill of the marginal farmer, e_t^*. Our assumption that the migration decision is irreversible, implies that the equilibrium sequence $\{e_t^*\}$ is non-decreasing.

Optimal choices of inputs and output by a farmer with skill level e are completely summarized by the first order conditions of profit maximization. The resulting demand for input functions for, each e, are denoted by [8]

$$m_t = m(q_t, c_t, w_t^F, e),$$

where $m \in \{k, h, a, \bar{n}\}$ indicates the input type, q_t is a vector of rental prices, and c_t is a vector of operating costs, and w_t^F denotes real wages in the farm sector.

Given that agricultural prices are largely set in world markets, and that domestic and total demand do not coincide, we impose as an equilibrium condition that the demand for land equal the available supply. Thus, land prices are endogenously determined.

3.1 Aggregate Implications

In this section we show how to compute the implications of our simple model for sector-wide aggregates. To this end we need to sum individual factor demands over all possible skill types.

3.1.1 The Number of Farms and Labor in Farms

Let the measure of *potential* farmers be $\bar{N}$. We assume that $\bar{\mathbf{N}} = \int_0^\infty \mu(de)$, for some measure μ. This measure captures the exogenous distribution of skills. let e_t^* be the 'marginal' farmer at time t; then, the number of farmers with ability levels less than or equal to e at time t is $\int_{e_t^*}^{e} \mu(ds)$, for $e \geq e_t^*$, and 0 for $e < e_t^*$. This distribution is time-varying and endogenously determined. The number of active farmers (and the number of farms)[9] at t is simply $\mathbf{N}_{ft} = \int_{e_t^*}^{\infty} \mu(de)$.

[8] To be precise, the demand functions depend on current and future prices. Even though the pure demand decision is static due to our assumption of perfect rental markets, the migration decision implies that future prices influence current demand through their impact on the identity of the farmers who remain in the rural sector, i.e. the level of e.

[9] Our model does not distinguish farms from farm operators.

Let, $\hat{e}_t$ be the value of e that satisfies

$$V_t(\hat{e}_t) \equiv V_t^U.$$

Then, e_t^* evolves according to $e_t^* = \min\left\{e_{t-1}^*, \hat{e}_t\right\}$. This formulation imposes the equilibrium condition that the the marginal farmer be indifferent between migrating or staying, or its identity is unchanged from the previous period. The condition $V_t(\hat{e}_t) = V_t^U$ is not a simple comparison. The reason is that $V_t(e)$ depends on all prices and, in our model, the price of land is determined endogenously (and a function of the distribution μ and the cutoff point e_t^*). Hence, obtaining $\hat{e}_t$ requires the computation of a fixed point at each t.

If each farmer has an endowment of $\hat{n}$ man/year equivalent (including family workers), the total number of man/year equivalent labor provided by farmers is $\hat{n}\mathbf{N}_{ft}$, while the total number of man/year individuals hired is[10]

$$\mathbf{N}_{st} = \int_{e_t^*}^{\infty} \max\left[\bar{n}(q_t, c_t, w_t^F, e) - \hat{n}, 0\right] \mu(de). \tag{1}$$

The ratio of hired to total labor is given by

$$\eta_t = \frac{\mathbf{N}_{st}}{\mathbf{N}_t} = \frac{\int_{e_t^*}^{\infty} \max\left[\bar{n}(q_t, c_t, w_t^F, e) - \hat{n}, 0\right] \mu(de)}{\int_{e_t^*}^{\infty} \bar{n}(q_t, c_t, w_t^F, e)\mu(de)} \tag{2}$$

3.1.2 Tractors, Horses and Land

The aggregate demand for tractor *services* at time t, $\mathbf{K}_t$ is given by

$$\mathbf{K}_t = \int_{e_t^*}^{\infty} k(q_t, c_t, w_t^F, e)\mu(de), \tag{3}$$

while the *number of tractors* purchased at t, m_{kt} is

$$m_{kt} = \frac{\mathbf{K}_t - (1 - \delta_{kt-1})\mathbf{K}_{t-1}}{v(x_t)}. \tag{4}$$

[10] This formulation assumes that if a farmer's demand for labor, $n_t(q_t, c_t, w_t^F, e)$ falls short of his endowment, $\hat{n}$, he can sell the difference in the agricultural labor market. This assumption is the natural analog of the perfect rental markets for tractors, horses, and land.

The law of motion for the stock of tractors (in units), $\mathbb{K}_t$, is[11]

$$\mathbb{K}_t = (1 - \delta_{kt-1})\mathbb{K}_{t-1} + m_{kt}. \tag{5}$$

We assume that horse services are proportional to the stock of horses and, by choice of a constant, we set the proportionality ratio to one. Thus, the aggregate demand for horses is

$$\mathbf{H}_t = \int_{e_t^*}^{\infty} h(q_t, c_t, w_t^F, e)\mu(de). \tag{6}$$

We let the price of land adjust so that the demand for land predicted by the model equals the total supply of agricultural land denoted by $\mathbf{A}_t$. Thus, given wages, agricultural prices and horse and tractor prices, the price of land, p_{at}, adjusts so that

$$\mathbf{A}_t = \int_{e_t^*}^{\infty} a(q_t, c_t, w_t^F, e)\mu(de). \tag{7}$$

3.2 Modeling Tractor Prices

From the point of view of an individual farmer the relevant price of tractor is $q_{kt}(\tau)$: the price of tractor services corresponding to a $t - \tau$ year old tractor. Unfortunately, data on these prices are not available. However, given a model of tractor price formation, it is possible to determine rental prices for all vintages using standard, no-arbitrage, arguments.

As indicated above, we assume that a *new tractor* at time t offers tractor services given by $\tilde{k}_t(t) = v(x_t)$, where $v(x_t)$ is a function that maps the characteristics of a tractor into tractor services. We assume that, at time t, the price of a new tractor is given by

$$p_{kt} = \frac{v(x_t)}{\gamma_{ct}}.$$

In this setting γ_{ct}^{-1} is a measure of markup over the level of quality. If the industry is competitive, it is interpreted as the amount of aggregate consumption required to produce one unit

[11] An alternative measure of the stock of tractors is given by $K_{t+1} = K_t + m_{kt+1} - m_{kt-T}$ were T is the lifetime of a tractor of vintage $t - T$. This alternative formulation assumes that tractors are of the one-hose shay variety and that after T periods they are scrapped.

of tractor services using the best available technology x_t.[12] However, if there is imperfect competition, it is a mixture of the cost per unit of quality and a standard markup. For the purposes of understanding tractor adoption we need not distinguish between these two interpretations: any factor —technological change or variation in markups— that affects the cost of tractors will have an impact on the demand for them. In what follows we ignore this distinction, and we label γ_{ct} as productivity in the tractor industry.

It is possible to show (see unpublished Appendix available from the authors) that no arbitrage arguments imply that

$$q_{kt}(t) = p_{kt}\left[1 - R_t(1)(1-\delta_{kt})\frac{\gamma_{ct}}{\gamma_{ct+1}}\right] + (1-\Delta_t)C(t+1, T-1), \tag{8}$$

where

$$\begin{aligned} \Delta_t &= \frac{v(x_t)(1-\delta_{kt})}{v(x_{t+1})}, \\ C(t+1, T-1) &\equiv \sum_{j=0}^{T-1} R_{t+1}(j) c_{kt+1+j}, \end{aligned}$$

given that T is the lifetime of a tractor, and c_{kt} is the cost of operating a tractor in period t.

This expression has a simple interpretation. The first term, $1 - R_t(1)(1-\delta_{kt})\frac{\gamma_{ct}}{\gamma_{ct+1}}$, translates the price of a tractor into its flow equivalent. If there were no changes in the unit cost of tractor quality, i.e. $\gamma_{ct} = \gamma_{ct+1}$, this term is just that standard capital cost, $(r_{t+1} + \delta_{kt})/(1 + r_{t+1})$. The second term is the flow equivalent of the present discounted value of the costs of operating a tractor from t to $t + T - 1$, $C(t + 1, T - 1)$. In this case, the adjustment factor, $1 - \Delta_t$, includes more than just depreciation: total costs have to be corrected by the change in the 'quality' of tractors, which is captured by the ratio $\frac{v(x_t)}{v(x_{t+1})}$.

To compute $q_{kt}(t)$ we need to separately identify $v(x_t)$ and γ_{ct}.[13] To this end we specified that the price of a tractor of model m, produced by manufacturer k at time t, p_{mkt}, is given by

$$p_{mkt} = e^{-d_t}\Pi_{j=1}^{N}(x_{jt}^{m})^{\lambda_j} e^{\epsilon_{mt}},$$

[12] We assume that the cost of producing 'older' vectors x_t is such that all firms choose to produce using the newest new technology.

[13] It is clear that all that is needed is that we identify the changes in these quantities.

where $x_t^m = (x_{1t}^m, x_{2t}^m, ...x_{Nt}^m)$ is a vector of characteristics of a particular model produced at time t, the d_t variables are time dummies, and ϵ_{mt} is a shock. This formulation is consistent with the findings of White (2000).[14] We used data on prices, tractor sales and a large number of characteristics for almost all models of tractors produced between 1919 and 1955 to estimate this equation. In the Appendix, we describe the data and the estimation procedure. Given our estimates of the time dummy, $\hat{d}_t$, and the price of each tractor, $\hat{p}_{mkt}$, we computed our estimate of average quality, $\bar{v}(x_t)$ as

$$\bar{v}(x_t) = \bar{p}_{kt}\hat{\gamma}_{ct},$$

where

$$\begin{aligned} \bar{p}_{kt} &= \sum_m s_{mkt}\hat{p}_{mkt}, \\ \hat{\gamma}_{ct} &= e^{\hat{d}_t}, \end{aligned}$$

with s_{mkt} being the share of model m produced by manufacturer k in total sales at time t. The resulting time-series for $\bar{v}(x_t), \hat{\gamma}_{ct}$ and $\bar{p}_{kt}$ are shown in Figure 3.

Even though the real price of a tractor does not show much of trend after 1920, its components do. Over the whole period our index of quality doubles, and our measure of productivity shows a substantial, but temporary increase in the 1940s, with a return to trend in the 1950s. In the 1920-1955 period γ_{ct} more than doubles. Thus, during this period there were substantial increases in quality and decreases in costs; however, these two factors compensated each other, so that the real price of a tractor shows a modest decrease.

4 Steady States and Calibration

At the steady state all variables are constant. We denote the interest rate by $R = (1+r)^{-1}$. The steady state version of the demand for factors is $m = m(q, c, w^F, e)$ for $m \in \{k, h, a, \bar{n}\}$. To

[14] Formally, we are assuming that the shadow price of the vector of characteristics x_t does not change over time. This is not essential, and the results reported by White (2000), Table 10, can be interpreted as allowing for time-varying shadow prices. Comparing the results in Tables 10 and 11 in White (2000) it does not appear that the extra flexibility is necessary.

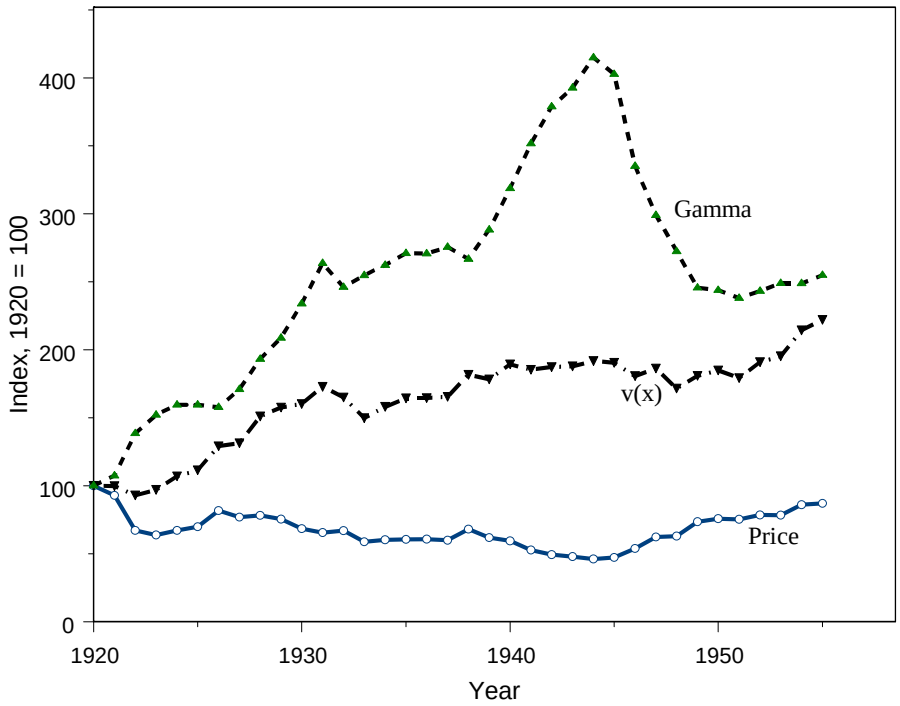

Figure 3: Tractor Prices, Quality and Productivity. 1920-1955. Estimation Results.

compute steady state aggregates, we use the endogenous distribution of skills of farm operators, which is completely summarized by e^* and μ.

Let the steady state profit flow be denoted $\pi(q, c, w^F, e)$. Then, the no-migration condition in the steady state is

$$\pi(q, c, w^F, e^*) = w^U - \frac{r\varphi}{1+r}.$$

Equilibrium in the land market requires that the appropriate version of (7) hold. Given this, it follows that average farm size , $\bar{a}$, is given by

$$\bar{a} = \frac{\int_{e^*}^{\infty} a(q, c, w^F, e)\mu(de)}{\mathbf{N}_f}. \tag{9}$$

Assuming that there is no change in tractor quality at the steady state, the number of tractors

follows from the appropriate version of (4) and (5) it is given by

$$\mathbb{K} = \frac{\int_{e^*}^{\infty} k(q, c, w^F, e)\mu(de)}{v(x)}. \tag{10}$$

The model's prediction for the demand for hired labor, the ratio of hired to total labor and horses follow from the steady state versions of (1), (2), and (6). The model's prediction for total farm output, $\mathbf{Y}$, is

$$\mathbf{Y} = \int_{e^*}^{\infty} y(q, c, w^F, e))\mu(de),$$

where $y(q, c, w^F, e)$ is the value of output of a farm with managerial skill e at the prices corresponding to the steady state.

4.1 Model Specification and Calibration

We consider the following specification of the farm production technology

$$\begin{aligned}
F^c(y_I, e) &= A_{ct} y_I^{\alpha_c} e^{1-\alpha_c}, \\
y_I &= F^y(z, n_y, a) = z^{\alpha_{zy}} n_y^{\alpha_{ny}} a^{1-\alpha_{zy}-\alpha_{ny}}, \\
z &= F^z(z_k, z_h) = [\alpha_z (z_k)^{-\rho} + (1-\alpha_z) z_h^{-\rho}]^{-1/\rho}, \\
z_k &= F^k(k, n_k) = [\alpha_k k^{-\rho} + (1-\alpha_k) n_k^{-\rho}]^{-1/\rho}, \\
z_h &= F^h(h, n_h) = A_h h^{\alpha_h} n_h^{1-\alpha_h}.
\end{aligned}$$

This formulation captures the idea that farm output depends on services produced by tractors, z_k, services produced by horses, z_h, labor, n_j, $j = y, h, k$, and managerial skills, e. We take a standard approach and use a Cobb-Douglas formulation except in two cases. We assume that the elasticity of substitution between tractors and labor in the production of tractor services is $1/(1+\rho)$. Since we assume that the elasticity of substitution between horses and labor is one, this formulation allows us to capture potential differential effects of a change in the wage rate upon the choice between tractor and horses. Second, we also assume that basic tractor services, z_k, and horse services, z_h, are combined with elasticity of substitution $1/(1+\rho)$ to produce power services, z. We specify that TFP grows at the rate γ.

We assume that the distribution μ is log-normal with mean $\hat{\mu}$ and standard deviation σ. We assume that $\beta = 0.96$, and that $\hat{n} = 2$. This last value is equivalent to specifying that the average farm family contributes labor equivalent to 2 workers. Since we could not find reliable estimates of φ we considered initially a value of φ equal to one year of average earnings.[15] We performed some sensitivity analysis and varied φ between a half and one and a half of average yearly earnings, and our findings remain essentially unchanged.

We take the process $\{A_{ct}\}$ to correspond to total factor productivity. Even though there are estimates of the evolution of TFP for the agricultural sector, it is by no means obvious how to use them. The problem is that, conditional on the model, part of measured TFP changes is due to changes in the quality of tractors, $v(x_t)$, as well as the rate of diffusion of tractors. Thus, in our model, conventionally measured TFP is endogenous. To compute (truly) exogenous TFP we used the following identification assumption: TFP is adjusted so that the model's prediction for the change in output between 1910 and 1960 match the data. This gives us an estimate of γ, which, in this case, is approximately 1.5% per year, which corresponds to an end-to-end change by a factor of 1.9. By way of comparison, the Historical Statistics reports that overall farm TFP grew by a factor of 2.3. Thus, around 17.4% of the increase in farm TFP between 1910 and 1960 can be accounted for by the diffusion of the tractor, and the steady increase in average quality.

The remaining parameters of the model were picked to minimize the differences between model and data for the year 1910. We used two sets of moments from the 1910 agricultural sector to calibrate the model. The first set of moments corresponds to input shares in agricultural output. The second set of moments is related to properties of the size distribution of farms. The details and the corresponding values are in the Appendix

The first two columns of Table 1 present the match between the model and U.S. data for our chosen specification for the year 1910. The match is fairly good in terms of most of the moments. The one exception is the share of horses to output. Relative to the U.S. economy our specification underpredicts the horse output ratio. It is not clear to us what is the reason. It is possible that in 1910 horses were used to produce services not directly related to farming (e.g. transportation),

[15] Kennan and Walker (2003) estimate that for high school graduates the cost of moving between urban areas is about $250,000. Thus, our assumption of one year in the baseline case is conservative.

and that our simple model is not well equipped to capture this.

	1910		1960		
Moment	Model	Data	Model	Data	Source
Land - share of output	0.198	0.2	0.198	0.2	Grilliches (1964)
Horses/output ratio	0.174	0.25	0.0066	0.01	Hist.Stat.of U.S.
Tractors/output ratio	0.0030	0.0031	0.133	0.135	Hist.Stat.of U.S.
Labor - share of output	0.47	0.5	0.381	0.401	Lebergott (1964)
C.V. of acres/farm	1.05	1.1	0.99	1.1	Hist.Stat.of U.S.
Labor - Hired/Total	0.27	0.24	0.24	0.26	Hist.Stat.of U.S.
$\bar{a}_{5-10}$	617	646	716	695	Hist.Stat.of U.S.
s_{5-10}	0.1	0.1	0.14	0.12	Hist.Stat.of U.S.
$\bar{a}_{10+}$	3414	3340	3662	3964	Hist.Stat.of U.S.
s_{10+}	0.19	0.19	0.38	0.49	Hist.Stat.of U.S.

Table 1: Match Between Model and Data, 1910 & 1960

The values of the calibrated parameters seem reasonable and, when there is evidence available, fall in the range of estimates from micro studies. Of particular importance for our purposes is the elasticity of substitution between horse services and tractor services. This elasticity —given by $1/(1+\rho)$— is calibrated to be equal to 2.5.[16] The model also does pretty well in matching the size distribution of farms.[17]

[16] Our preferred value is slightly higher than the value of 1.7 estimated by Kislev and Petersen (1982). However, they completely ignored horses and their estimate is likely to be some weighted average of the two elasticites of substitution: labor and capital and labor and horses.

[17] The model produces a continuous distribution of farms (by farm size). We put the distribution in three bins (0-499, 500-999, and 1000+) to match the evidence on acreage. We use this distribution to compute the moments that we report. To compute mean conditional average acreage per farm we use (both for the model and the data) a richer continuous distribution.

5 Was Diffusion Too Slow?

The results for 1960 indicate that the model does a reasonable job of matching some of the key features of the data. However, they are silent about the model's ability to account for the *speed* at which the tractor was adopted.

Was diffusion too slow? To answer this question, the entire dynamic path from 1910 to 1960 needs to be computed. To do this, we took the observed path for prices (p_k, p_h, p_c, w, w^F), operating costs (c_k, c_h, c_a) and depreciation rates $(\delta_k, \delta_h, \delta_a)$, and used them as inputs to compute the predictions of the model for the 1910-1960 period.[18] At the same time, we adjusted the time path of TFP so that the model matches the data in terms of the time path of agricultural output, the analog of our steady state procedure. This helps to get the scale right along the entire transition. This exercise is computationally very intensive as it requires solving for the fixed point in the sequence of TFPs from 1910 to 1960, in addition to calculating the equilibrium in the land market in each period.

The predictions of the model (and the relevant data for the U.S.) for the number of tractors and horses is depicted in Figure 4. The model does a remarkable job of tracking the actual diffusion of the tractor and the decline of the horse.

To provide a quantitative dimension of goodness of fit, we define a distance between model and data, ϕ, given by

$$\phi = 1 - \frac{d(x, y)}{d(y, \bar{y})},$$

where

$$d(x, y) \equiv \sum_{t=0}^{T} (x_t - y_t)^2,$$

and x is a vector of predictions, while y is a vector (of equal length) that includes observed (U.S.) values. The sample mean of this vector is denoted $\bar{y}$. Thus, ϕ seems a reasonable measure of 'goodness of fit' for models that aim to match transition data. Note that if the model is no better

[18] We use five-year moving averages for all these sequences. For the years 1910 and 1960, we use actual data (remember that these dates are viewed as steady-states). For all other years, the five year average was constructed as the average of the the year in question, the two years before and the two years. In a sense, using a five year average substitutes for the lack of adjustment costs in the model.

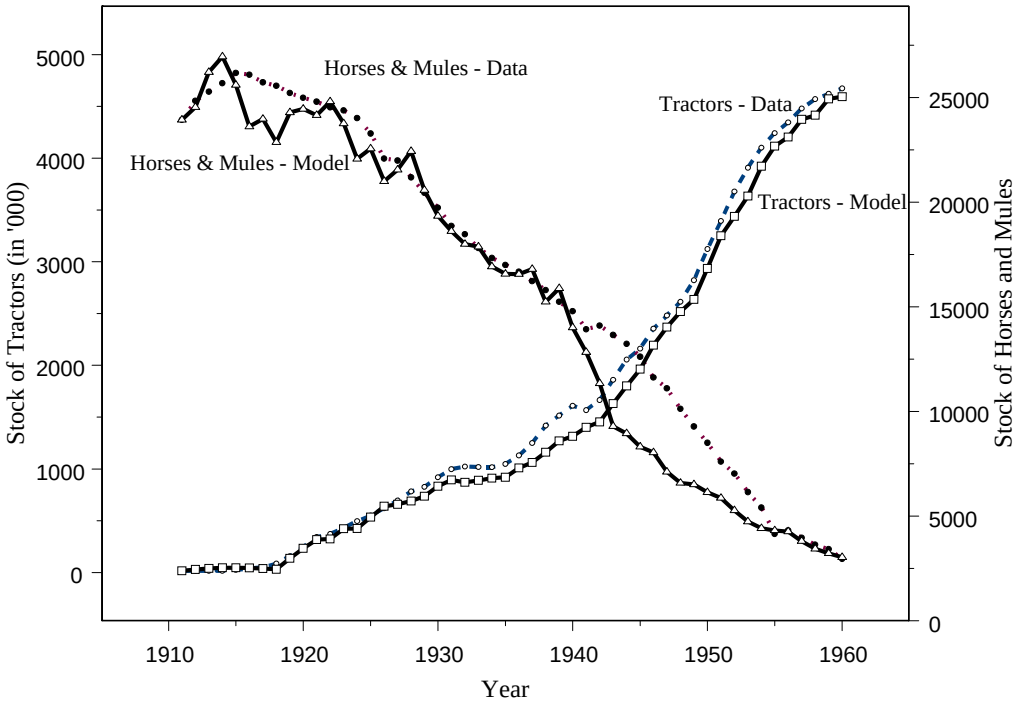

Figure 4: Transitional Dynamics, 1910-1960 - Tractors and Horses

at predicting the data than the sample mean, $\phi = 0$, while if the model fits the data perfectly $\phi = 1$. We computed the measure ϕ for tractors, horses and employment. The results are in Table 2

A large fraction of the variability around the sample mean for both tractors and horses is accounted for by the model. In addition, the correlation coefficients between the model and the data are very high.

How does the model perform along other dimensions? Figure 5 depicts the model's predictions (and the U.S. values) for employment in the agricultural sector. The model's estimates track the data quite well and, in particular, they capture the sharp decreases in employment in agriculture

Series	ϕ	Correlation	Mean (US)	Mean (Model)
Tractors	0.99	0.999	1669	1559
Horses	0.94	0.982	16430	15254
Employment	0.83	0.974	19.75	18.4

Table 2: Measures of Goodness of Fit

in the 1940s and 1950s.[19] The fact that the model is able to caputre most of the rural to urban migration over the period in question suggests that push factors (the replacement of muscle for machines) were very important in contributing to urbanization. This mechanism is quite different from, say Lucas (2004) who analyzes the impact of externalities in accounting for urbanization. Our results suggest that one need not resort to such externalities in order to generate the migration flows from the rural to the urban sector we see in the data.[20]

Figure 6 plots the predictions of the model for the coefficient of variation of the variable 'acres per farm'. The corresponding population data from the U.S. is included as well. The baseline specification generates estimates of the changes in the coefficient of variation of the variable 'acres per farm' that also follow the time path for the U.S. Interestingly enough, both model and data predict an inverted U-shape pattern, with the period of high migration as a period of high relative inequality in the farm distribution.

Figure 6 also displays the predictions of the random migration model for the coefficient of variation of farm size. Contrary to the data (and the baseline model), ignoring selection results in a downward trend. We view this as additional evidence against this specification.[21]

[19] In the case of employment the corresponding ϕ is 0.84.

[20] The consideration of the size distribution of farms and rural to urban migration allows us to get additional implications with which to examine the performance of the model. There are two other reasons we added this feature. First, it helps us to calibrate the model by providing us with more moments to match. Second, it also helps us in accounting for TFP, in that if migration is selective as we have in the baseline case, the framework requires less of an increase in total factor productivity than a comparable framework without this heterogeneity. We discuss this in more detail in the sub-section labeled "Selective versus Randon Migration".

[21] As shown in the unpublished appendix, the coefficient of variation corresponding to the continuous version of the random migration model is constant over time. Thus, the decreasing trend is driven by the 'discretization' of the variable in our three size categories. Note, however, that this is also how the coefficient of variation corresponding

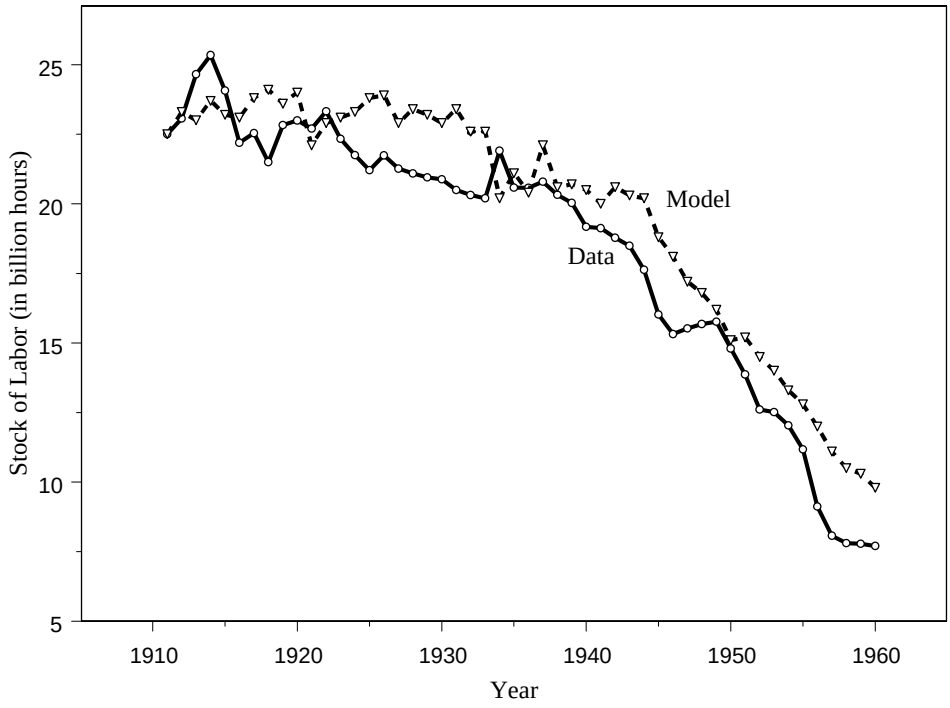

Figure 5: Transitional Dynamics 1910-1960 - Employment in Agriculture

6 The Role of Wages and Quality Changes

The previous section established that, relative to a standard equilibrium model, adoption of the tractor by U.S. farmers was not 'slow.' A key innovation of our setup is that we explicitly took into account the role of substitution along an isoquant (as captured by changes in the prices of inputs), as well as quality upgrades. In this section we explore the role that each of the factors we identified above played in determining the equilibrium speed of adoption. We do this by using the model to analyze a series of counterfactuals. In each case, TFP is adjusted so that the alternative specification perfectly matches agricultural output.

to the U.S. is computed.

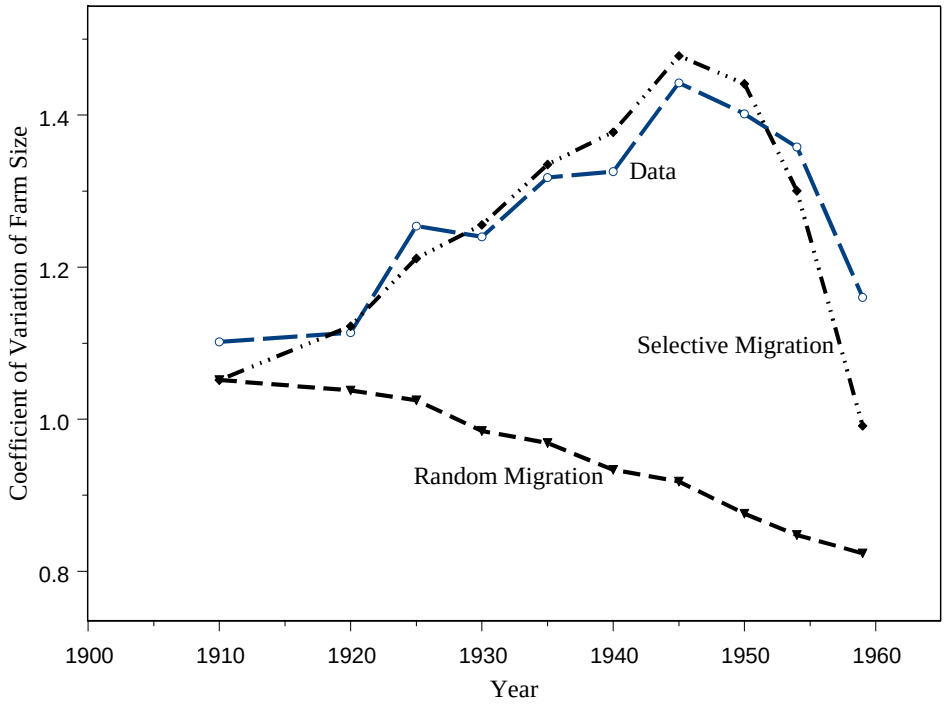

Figure 6: Transitional Dynamics 1910-1960. Coefficient of Variation - Selective vs. Random Migration

The Effect of Wages In Figure 7 we report the predictions of the model under the assumption that wages are fixed at their 1910 level. In this case, the model predicts that adoption would have been even slower. This specification underpredicts tractor adoption by about 30% in the late 1950s. An alternative scenario is one in which wages grow at a constant annual rate - so that the increase in wages between 1910 and 1960 is exactly the same as in the baseline model. The results are in Figure 8. In this case, the model is consistent with the view that adoption was slow, particularly during the 1930s and 1940s. Specifically, this version predicts that the stock of tractors should have more than 50% higher during the 1930s. Since wage changes have a first order effect on the relative cost of operating the tractor vs. the horse technology, ignoring the

Figure 7: Wages held constant at 1910 level

time path of wages results in incorrect predictions.

The Effect of Quality Changes Our model emphasizes that a 'tractor' in 1960 is not the same capital good as a 'tractor' in 1920. Not only there are significant differences in the quality of each tractor, but the cost of operating a tractor per unit of quality also vary significantly. To ascertain the quantitative importance of this dimension we conducted two counterfactual experiments that ignore quality changes. In one experiment, see Figure 9, we assumed that there is no quality increase. That is, the level of quality is fixed at its 1910 level. In this case, the model severely underpredicts the stock of tractors. This is the case in all decades, but it is particularly severe in pre 1940 period, the shortfall is close to 50%.

Figure 8: Constant Wage Growth

At the other end, if one were to treat a 'tractor' in 1910 as equivalent to a 'tractor' in 1960, then the conclusion is that adoption was slow. Figure 10 shows the results. In this case, according to the model, the U.S. agricultural sector was using only half as many tractors as profit maximization would have prescribed. In this case, there is also slow adoption.

Discussion: The fact that these two factors play a major role in accounting for the diffusion of the tractor is comforting in that these forces should be generalizable. Gradual quality change is certainly an important factor in the diffusion of many innovations - early incarnations of the new technology are pretty crude and slowly evolve with time.[22] While quality change has been

[22] Bils and Klenow (2001) estimate that quality has been increasing at about 1.5 percent per year for the past 20 years or so which is higher than the .5 percent annual rate of quality growth that the U.S. Bureau of Labor Statistics

Figure 9: Quality held constant at the 1910 level

considered before, they have not been modeled in the gradual fashion in which we model it. The close tie up between the our estimation and our model simulation is a feature worthwile emphasizing. Furthermore, most other papers (see, for instance, Greenwood, Seshadri and Yorukoglu, 2004) model the evolution of quality as a one shot event, moving up to the frontier right away - even though they assume a gradual decline in the price of capital. Our results make it very clear that such a consideraton would lead the researcher to conclude, rather incorrectly, that diffusion was slow! Finally, the fact that rising wages induce a substitution away from the labor intensive technology to a rather capital intensive technology should also have wide appeal. For, as wages rise along a balanced growth path, the planner would have an incentive to invest in the creation of

uses in adjusting its inflation figures.

Figure 10: Instantaneous jump in quality to the 1960 level

labor saving innovations and consequently replace labor for capital. For instance, Acemoglu and Zilibotti (2001) argue that differences in relative prices (of skill) generate differences in the direction of technological change. Here, we argue that differences in relative prices generate differences in the pattern of adoption of new technologies.

One of the key mechanisms identified in the prevailing literature on technology diffusion is that if old capital and new capital are complementary inputs, the marginal product of investment depends not only on the vintage of technology but also on the amount of old capital available for that specific vintage. Even when new technologies are available, people invest in old technologies if there exist abundant old capital for these technologies. As a consequence, diffusion of new technologies is slow. This is the mechanism at work in both Chari and Hopenhayn (1991) and many subsequent papers. The mechanisms at work in our model generate a slow pattern of adoption even if the services obtained from the two types of capital are substitutes, despite the consideration of a frictionless set-up.

7 The Role of Other Factors

We explored the sensitivity of the results to changes in a number of other factors. For brevity, we do not report the detailed results. Our analysis describes the effects of other 'counterfactuals' when TFP is adjusted so that each model matches the observed growth in agricultural output between 1910 and 1960.

Selective vs. Random Migration It is possible to show (see the unpublished Appendix for a formal proof) that if the production function is Cobb-Douglas in managerial skill and other factors (as is the case in our model), *any* aggregate level of input use (and total output) generated by the baseline model can be replicated by the random migration version, given an appropriate adjustment in TFP. Thus, to ascertain the ability of the model to match the data we need to consider moments that depend on the size distribution. Along these lines, the random migration model fails in two dimensions: it underpredicts the coefficient of variation of 'acres per farm' by 25% (0.82 vs. 1.1), and it overpredicts the ratio of hired to total labor. More importantly, it gives

counterfactual predictions for some moments of the distribution of farm size.

The Role of Horse Prices Recent research on the topic of adoption of tractors has emphasized that adjustment of horse prices delayed the diffusion of tractors (see Olmstead and Rhode (2001)). In the context of this model, fixing horse prices at their 1910 levels has hardly any effect on adoption. The reason is simple: horse prices are a relatively unimportant component of the cost of operating the horse technology. Should we conclude that explicitly modeling the fact that farmers had a choice between an 'old' and a 'new' technology is an unnecessary feature of the model? No. The reason is simple: had we ignored horse, we would have had only a minor impact from the change in wages, and this would have severely limited the model's ability to match the data.

Elasticity of Substitution Our specification of the technology is such that, at our preferred parameterization, the elasticity of substitution between tractors and labor is 2.5, while the elasticity of substitution between horses and labor is one. In order to quantitatively assess the importance of this specification, we studied a version of the model in which ρ is set equal to 0. In this case, the model severely underpredicts the diffusion of the tractor. The reason for this result is simple: The Cobb-Douglas functional form implies constant input shares. In the absence of spectacular price decreases in the own price —and tractor prices showed a large, but not spectacular decrease over this period — the model predicts modest increases in the quantities demanded.

Changes in the Share of Managerial Skills The assumption that managerial skills receive a non-zero fraction of total revenue plays a significant role in our model, as it has an impact on migration decisions. We considered a specification that significantly reduces the share of profits that accrue to skill. Specifically, we studied the case in which the share of non-managerial factors, α_c, equals 0.999. The model underpredicts the number of tractors by 13% and, more importantly, predicts a huge increase in average farm size. While in the data, the average acreage per farm increases by a factor of 2.13 between 1910 and 1960, this specification predicts an increase four times as large.

8 Conclusions

The frictionless neoclassical framework has been used to study a wide variety of phenomena including growth and development.[23] However, the perception that the observed rate at which many new technologies have been adopted is too slow to be consistent with the model, has led to the development of alternative frameworks which include some 'frictions.'

In this paper we argue that a careful modeling of the shocks faced by an industry suggests that the neoclassical model can be consistent with 'slow' adoption.[24] Since most models with 'frictions' are such that the equilibrium is not optimal, the choice between standard convex models and the various alternatives has important policy implications. It is clearly an open question how far our results can be generalized. By this, we mean the idea that to understand the speed at which a technology diffuses it is necessary to carefully model both the cost of operating alternative technologies and the evolution of quality. However, even without conducting a careful analysis, it is not difficult to point to several examples that suggest that the forces that we emphasize play a role more generally.

Consider first, the diffusion of nuclear power plants. While the technology to harness electricity from atoms was clearly available in the 1950s, diffusion of Nuclear power plants was rather 'slow'. Rapid diffusion did not take place until 1971. In 1971, Nuclear's share of total electricity generation was less than 4%. This number shot up to 11% by 1980 and around 20% by 1990 and remained at that level. What was the impetus for such a change? The obvious factor was the oil shock of the 1970s which dramatically increased the real price of crude oil and induced a substitution away from the use of fossil fuels to uranium. Furthermore, when the price of oil came down, the United States stopped building nuclear reactors. The other factor that played an important role in putting a stop to the diffusion of nuclear power plants is the high operating cost associated with waste disposal. Nuclear power plants have generated 35000 tons of radioactive waste, most

[23] It has even been used as a benchmark by Cole and Ohanian (2004) in the study of the great depression.

[24] More generally, our model suggests that to understand the adoption of a technology in a given sector it may be critical to model developments in another sector. To see this, consider, as in this paper, two technologies that use a given input in different quantities. In this setting shocks to another sector that uses the same input will induce price changes which, in turn, will affect technology choices. Thus, general equilibrium effects can induce slow adoption.

of which is stored at the plants in special pools or canisters. But the plants are running out of room and until a permanent storage facility is opened up, the diffusion of nuclear power plants will proceed slowly. All this suggests that changes in the price of substitutes (oil) and changes in operating costs can go a long way toward accounting for the diffusion of nuclear power plants.

A second example is the case of diesel-electric locomotives. The first diesel locomotive was built in the U.S. in 1924, but the technology did not diffuse until the 1940s and 1950s. It seems that the key factor in this case was a substantial improvement in quality: increased fuel efficiency relative to it's steam counterpart and possibly more important, reduced labor requirements. Since, as we documented in the paper, wages rose substantially during World War II, quality improvements reduced the cost of operating the diesel technology relative to the steam technology.

Of course, a couple of examples, no matter how persuasive they appear, cannot 'prove' that factors that are usually ignored in the macro literature on adoption are important. However, at the very least, they cast a doubt on the necessity of 'frictions' in accounting for the rate of diffusion of new technologies.

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9 Appendix

9.1 Data Sources

This section details the available data, the sources which they were obtained and what they were used for. The data were used to calibrate the model and to compare the model and the data.

Income and Output

Farm Output: HS Series K 414 - used to compute the endogenous TFP in getting the model to match the data in terms of its predictions for output.

Value of Gross Farm Output: HS Series K 220-239 - used to compute factor shares.

Land

Number of farms: HS Series K4 - used to compute average size of farm

Land in Farms: HS Series K5 and K8 - used to compute average size of farm

Distribution of farm-acreage: HS Series K 162-173 - used to compute the C.V. of average farm size

Labor

Employment in farms (total and hired labor): HS Series K174, K175, K176 - used to compute hired labor as a fraction of total labor.

Man-hours Employed: HS Series K 410 - used to compute Labor's share of income and to compare model and data.

Wage Rates: Rural wages from HS Series K 177; Urban wages from HS Series D 802 - used to compute labor's share of farm income and as an exogenous driving process

Capital - Tractors and Horses

Number of Tractors on farms: HS Series K 184 - used to compute tractor's share of farm income

Number of Horses and Mules on farms: HS Series K 570, K572 - used to compute horses's share of farm income

Depreciation Rates and Operating Costs for Tractors: For the period 1910-1940, we used data from USDA. *Income Parity for Agriculture, Part II.* For the period 1941-1960, we used data from USDA, Agricultural Statistics - used as exogenous driving processes

Horse Prices: Data provided by Paul Rhode - used to compute horses's share of farm income and as an exogenous driving process

Tractor Prices: From 1920 to 1955, we used data from on our hedonic estimations. These estimations were based upon data on tractor prices and characteristics kindly provided to us by William White and augmented to include additional characteristics from Dunning (2000). For the period 1910-1919, and 1956-1960, we extrapolated the data using our estimation and data on average price of tractor available from the USDA, Agricultural Statistics. The exact manner in which this was done is described in the Appendix. This series is used to compute tractor's share of farm income and as an exogenous driving process.

9.2 Tractor Prices

9.2.1 Estimation of Tractor Prices

In order to compute the user cost of tractor services, we need to estimate the effect that different factors have upon tractor prices. Our basic specification is

$$\ln p_{mkt} = -d_t + \sum_{j=0}^{N} \lambda_j \ln x_{jt}^m + \epsilon_{mt},$$

where p_{mkt} is the price of a model m tractor produced by manufacturer m at time t, the vector $x_t^m = (x_{1t}^m, x_{2t}^m, ...x_{Nt}^m)$ is a vector of characteristics of a particular model produced at time t, the d_t variables are time dummies, and ϵ_{mt} is a shock that we take to be independent of the x_{jt}^m variables and independent across models and years. We estimated the previous equation by OLS using a sample of 1345 tractor-year pairs covering the period 1920-1955. The basic data comes from two sources. William White very generously shared with us the data he collected which includes prices, sales volume and several technical variables. A description of the sample can be found in his dissertation, White (2000). We complemented White's sample with additional technical information obtained from the Nebraska Tractor Tests covering the 1920-1960 period, as reported by Dunning (1999). The variables in the x vector included technical specifications as well as manufacturer dummies. In the following table we present the point estimates of the technical variables.

Variable	Estimate	t	Variable	Estimate	t
FuelCost	0.079	2.73	Row Crop (D)	-0.024	-2.05
Cylinders	0.030	0.61	High Clear (D)	0.008	0.31
Gears	0.108	3.82	Rubber Tires (D)	0.155	5.04
RPM	-0.156	-3.08	Tractor Fuel (D)	-0.153	-2.68
HP	0.573	19.92	Kerosene-Gasoline (D)	0.034	1.55
Plow Speed (Test)	0.111	2.25	Distillate-Gasoline (D)	-0.023	-1.40
Slippage (Test)	-0.021	-2.08	All Fuel (D)	-0.092	-1.70
Length	-0.116	-2.13	Diesel-Gasoline (D)	0.037	1.15
Weight	0.226	7.19	Diesel (D)	0.089	1.85
Speed	-0.055	-1.53	LPG (D)	-0.199	-1.91

Table 3: Regression Results. Point Estimates and t-statistics. A (D) denotes a dummy variable.

In addition, we included 15 manufacturer dummies and 35 time dummies. We selected the variables we used from a larger set, from which we eliminated one of a pair whenever the simple correlation coefficient between two variables exceeded 0.80. We experimented using a smaller set of variables as in White (2000), but our estimates of the time dummies were practically identical.[25]

Our data covers the period 1920-1955. However, the period we are interested in studying is 1910-1960. Thus, we need to extend the average price and the time dummies to cover the missing years. The price data for 1910-1919 come from Olmstead and Rhode (2001), and it corresponds to the price of a 'medium tractor'. For the period 1956-1960 we used the price of an average tractor as published by the USDA. Inspection of the pattern of the time dummies —the line labeled Gamma in Figure 3— suggest a fairly non-linear trend. If we exclude the war-time years, it seems as if productivity was relatively constant since the mid 1930s. Thus, for the 1956-1960 period we

[25] When all the variables are included, the predictions of the model for the estimated values of $v(x)$ and γ_{ct} are virtually identical. We decided to use this non-standard criteria to eliminate variables, in order to report significant coefficients. In the case in which all the variables are included, serious collinearity problems result in (individual) coefficients that are very imprecisely estimated.

assume that there was no change in γ_{ct}. The situation is quite different from 1910 to 1920, as this is a period of rapidly falling prices. We estimated the time dummies for the period 1910-1919 from a regression of the time dummies over the 1920-1935 period (before they 'stabilize') on time and time square. Our estimated values imply that most of the drop in tractor prices in this period is due to increases in productivity (more than 80%). This is consistent with the accounts that important changes in the tractor technology did not occurred until the 1920s.

9.3 Calibration

To calibrate the model, the following moments were used:

1. *Input moments.* The mapping between observed input ratios and shares and the corresponding objects in the model is given by:

$$\begin{aligned}
\alpha_c(1-\alpha_{zy}-\alpha_{ny}) &= \textit{land share of output}, \\
\frac{p_h \int_{e^*}^{\infty} h(q,c,w^F,e)\mu(de)}{\int_{e^*}^{\infty} y^*(q,c,w^F,e))\mu(de)} &= \textit{horses/output ratio}, \\
\frac{p_k \int_{e^*}^{\infty} k(q,c,w^F,e)\mu(de)}{\int_{e^*}^{\infty} y^*(q,c,w^F,e))\mu(de)} &= \textit{tractors/output ratio}, \\
\frac{w^F \int_{e^*}^{\infty} \bar{n}(q,c,w^F,e)\mu(de)}{\int_{e^*}^{\infty} y^*(q,c,w^F,e))\mu(de)} &= \textit{labor share of output}, \\
\frac{\int_{e^*}^{\infty} \max[\bar{n}(q,c,w^F,e)-\hat{n},0]\mu(de)}{\int_{e^*}^{\infty} \bar{n}(q,c,w^F,e)\mu(de)} &= \textit{hired/total labor}
\end{aligned}$$

2. *Size Distribution.* Since heterogeneity of farmers plays such an important role in our story, we required the model to match as many moments of the distribution of the variable '*acres per farm*' —our measure of firm size— as we could find. To ensure consistency over the 1910-1960 period we restricted ourselves to moments for which time series evidence is available in a consistent manner. The best information that we could obtain partitions the data into four bins. It includes information on the number of farms for establishments of 49 acres or less, 50-499 acres, 500-999 acres and 1,000 or more acres. We decided to merge the first two categories, since we suspect that forces other than agricultural prices affect the number of very small farms (less than 49 acres). In addition to this information, we were able to

find some moments of the continuous size distribution. Specifically, we have information on average farm size conditional on being in a certain size category. Let $\tilde{e}_k$ be the skill level of a farmer who operates a farm of size $k \times 10^2$. Thus, $\tilde{e}_k$ solves

$$a(q, c, w^F, \tilde{e}_k) = k \times 10^2.$$

Then the average acreage of a farm, conditional on being in, say, the 500-999 acre category is

$$\bar{a}_{5-10} = \frac{\int_{\tilde{e}_5}^{\tilde{e}_{10}} a(q, c, w^F, e)\mu(de)}{\mu(\tilde{e}_{10}) - \mu(\tilde{e}_5)},$$

while the share of land in farms in the 500-999 acre category is

$$s_{5-10} = \frac{\int_{\tilde{e}_5}^{\tilde{e}_{10}} a(q, c, w^F, e)\mu(de)}{\int_{e^*}^{\infty} a(q, c, w^F, e)\mu(de)}.$$

We also matched the second moment of the distribution. For simplicity —and given that the mean is matched by assumption— we chose to match the coefficient of variation. Thus, the model also matches

$$\frac{[\int_{e^*}^{\infty} [a(q, c, w^F, e) - \bar{a}]^2 \mu(de)]^{1/2}}{\int_{e^*}^{\infty} a(q, c, w^F, e)\mu(de)} = \ C.V. \ of \ \ Farm \ Land.$$

In order to match the average farm size in 1910, $\bar{a}$, we adjusted total land area ($\mathbf{A}$ in the model). Thus, we used a 'free' parameter to match this statistic.[26] Note, however, that total land area in 1960 is **not** a free parameter. We used data on Land in Farms (from the Historical Statistics) to estimate the supply of land in 1960 —using our units— as

$$\mathbf{A}_{60} = \mathbf{A}_{10} \ \times \ measured \ change \ in \ land \ in \ farms.$$

3. The calibration proceeds as follows. We choose the parameters so that the model —evaluated at the 1910 prices— matches the 10 moments we obtained from the data. Since computing the model's predictions requires a fixed point in the endogenously chosen 'marginal' farmer, e^*, calibration is computationally intensive, and we were unable to match the data exactly. Table 4 spells out the parameters used to calibrate the model.

[26] Alternatively, we could have endogeneized $\bar{N}$, the total mass of potential farmers, to match land. In our numerical exercise we set $\bar{N} = 1$.

Parameter	A_h	α_c	α_{zy}	α_{ny}	α_z	α_k	α_h	ρ	$\hat{\mu}$	σ	β	φ	$\hat{n}$	γ
Value	3.7	0.86	0.37	0.4	0.55	0.72	0.6	-0.6	4	1.72	0.96	223	2	.015

Table 4: Calibration